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Current Commentary

Current Commentary: Thorium-based nuclear power

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1. Thorium instead of uranium?

It may well turn out that thorium is a better nuclear fuel than uranium, since it offers the advantages that: (1) it has around four times the abundance of uranium on Earth, overall; (2) practically 100% of it can be bred into the fissile nuclear fuel ^{233}U; (3) smaller amounts of plutonium and other transuranic elements are produced than is the case from uranium fuel; (4) the thorium fuel cycle might be used to consume plutonium, thus reducing the nuclear stockpile, while converting it into useful energy. There was a conference held in Chicago, in May 2013, on "5th Thorium Energy Alliance – Future of Thorium, Energy and Rare Earths." http://thoriumenergyalliance.com/index.html.

Thorium[1] is a naturally occurring radioactive element, with the chemical symbol *Th* and an atomic number of 90. The mineral, now known as thorite, was discovered in 1828 by the Norwegian priest and mineralogist, Morten Thrane Esmark. In the same year, the element, thorium, was identified in the material by the Swedish chemist, Jöns Jakob Berzelius, who named it after Thor, the Norse god of thunder. Thorium is found in soils at an average concentration of 6 parts per million (p.p.m.), and in most rocks. In higher concentrations, thorium occurs in several kinds of mineral, of which the most common is the rare earth phosphate mineral, monazite, which contains up to about 12% thorium phosphate, but 6–7% as an average. World monazite resources are estimated to be of the order of 12 million tonnes, two-thirds of which are in heavy mineral sands deposits on the south coast and east coast of India. The world total of economically extractable thorium is estimated at around 2.61 million tonnes (Table 1)[2], and Australia and the USA top the list with 489,000 and 400,000 tonnes

Table 1 *World sources of thorium (2007)[2]*

Country	Tons	% of total
Australia	489,000	19
USA	400,000	15
Turkey	344,000	13
India	319,000	12
Venezuela	300,000	12
Brazil	302,000	12
Norway	132,000	5
Egypt	100,000	4
Russia	75,000	3
Greenland	54,000	2
Canada	44,000	2
South Africa	18,000	1
Other countries	33,000	1
World total	2,610,000	

of it, respectively. Norway has 132,000 tonnes of thorium, which adds to the large energy reserves of this country in terms of gas, oil and coal, not to mention hydropower, from which 99% of its electricity is generated. Other than negligible amounts of a few highly radioactive isotopes, thorium occurs exclusively as ^{232}Th. Although ^{232}Th is not fissile in itself, it can be converted to a fissile fuel in the form of ^{233}U, via the absorption of slow neutrons. Hence, as is the case for ^{238}U, ^{232}Th is "fertile" and may be bred into a nuclear fuel, which in the former case is ^{239}Pu.

Kirk Sorensen, a major proponent for the development of thorium power (http://energyfromthorium.com/), particularly in conjunction with the liquid fluoride reactor, LFR (also called the molten salt reactor, MSR) has offered the following[3], in regard to the essential differences between the two elements ^{232}Th and ^{239}Pu, as pertaining to their use in nuclear weapons or "dirty bombs":

> *"There are several reasons why U-233 is unattractive for nuclear weapons. One is that it doesn't produce as many neutrons in fast fission as Pu-239. Another is that its properties in very fast fission (such as a nuclear detonation) are poorly understood.*
>
> *But the biggest deterrent is that U-233 is inevitably contaminated with U-232 during its formation. It is highly impractical to separate them. And U-232 has a short half-life (~80 years) and a decay chain that includes the strong gamma emitter Tl-208. A few months after the U-233 is isolated from parent materials, the decay chain of U-232 begins to set up and the strong 2.3 MeV gammas of Tl-208 would irradiate the weapon, its electronics, as well as providing an easily-detected alert to the world that U-233 was present in a location.*
>
> *In contrast, the alpha decay of U-235 and Pu-239 are rather easily shielded, making clandestine transport of these weapons much easier, as well as allowing long-term storage with relatively little damage to the electronics of the device. With all these drawbacks, it is not surprising that U-233 has not been utilized in operational nuclear weapons. This inherent physical resistance to proliferation is a powerful argument for the adoption of thorium as a basic nuclear energy source."*

Since 100% of naturally occurring thorium can be converted into nuclear fuel (^{233}U) (Scheme 1), compared with the mere 0.7% of natural uranium that is fissile, *i.e*. ^{235}U, which is enriched by centrifugation or gaseous diffusion of uranium hexafluoride (UF_6), there is an obvious advantage[4]. Fuel for fuel, the advantage factor is around 30, in favour of thorium – since that from uranium is enriched to around 3% in ^{235}U – but this is counterbalanced by a depletion of this isotope in the remaining material, which is generally referred to as "depleted uranium" and sometimes is used in armaments and missiles. Roughly one-third of the power from a U-fuelled fission reactor is due to the fissioning of ^{239}Pu, generated *in situ* from ^{238}U, and so we can ascribe an overall advantage factor of *ca* 100 for thorium over uranium, though a value of 250 is claimed, when enrichment "losses" for ^{235}U / ^{238}U and higher efficiencies for thorium reactors are included (http://energyfromthorium.com/). It might be argued that the rest (^{234}U has an abundance of only about 0.0055%) of the 100% of the uranium (^{238}U) can be converted to plutonium in a similarly effective manner, but this requires fast neutrons in a fast breeder reactor: a technology with certain disadvantages, including the need to handle plutonium – a very toxic material, although there are as yet no reported casualties from it – and fears over its proliferation. Often cited too, is the potential fire hazard of pyrophoric liquid sodium, which is often used as a coolant, although helium, lead or a lead–bismuth alloy have all been proposed as alternatives. Thus, if the latter method is to be

avoided, considerably more energy might be extracted from thorium than from an equivalent quantity of uranium. Even on the basis of the "known" 2.61 million tonne reserve of thorium (Table 1), a simple sum indicates that it could provide nuclear power for: [2.61 million (tonnes of thorium) / 4.02 million (tonnes of uranium)] × 100 (enhancement factor in favour of Th over U) × 62 years (*i.e.* the current estimate based on uranium[5]) = *ca* 4,000 years. Even if we made all our electricity from thorium (currently, 13.5% of world electricity is from nuclear power), there would still be around 500 years' worth, and so if governments are intent on nuclear expansion to obviate global warming, thorium may well prove advantageous.

$$n + {}^{232}_{90}\mathrm{Th} \longrightarrow {}^{233}_{90}\mathrm{Th} \xrightarrow{\beta^-} {}^{233}_{91}\mathrm{Pa} \xrightarrow{\beta^-} {}^{233}_{92}\mathrm{U}$$

Scheme 1 *Conversion of thorium into nuclear fuel (^{233}U)*

Ralph W. Moir and Edward Teller (dubbed[6] as the "father of the 'H' bomb" and the real "Dr Strangelove"), made a study of thorium-based nuclear power from which they concluded that research should be reinitiated after being abandoned for more than three decades[7]. There is a comprehensive review published by the International Atomic Energy Agency (IAEA) on the subject of thorium-based nuclear power[8].

2. The thorium age waits in the wings

There are different ways in which energy might be extracted from thorium, one of which is the accelerator-driven system (ADS)[9]. Such accelerators need massive amounts of electricity to run them, as all particle accelerators do. As noted below, an alternative means to use thorium as a fuel is in a liquid fluoride reactor (LFR), also termed a molten salt reactor, which avoids the use of solid oxide nuclear fuels. Indeed, China has made the decision to develop an LFR-based thorium-power programme, to be active by 2020. However, the matter of thorium reactors is not straightforward. Neutrons may be produced from heavy elements by spallation, using high-current, high-energy accelerators or cyclotrons. In this process, a beam of high-energy protons (> 500 MeV) is directed at a high-atomic number target (*e.g.* tungsten, tantalum, depleted uranium, thorium, zirconium, lead, lead-bismuth, mercury) by which means up to one neutron can be produced per 25 MeV of the proton beam energy. A 1000 MeV beam will create 20 – 30 spallation neutrons per proton, to be compared with 200 – 210 MeV released in the fission of one nucleus of ^{235}U or ^{239}Pu. If the spallation target is surrounded by a blanket assembly of nuclear fuel, containing *e.g.* ^{235}U or ^{239}Pu (or ^{232}Th which can breed to ^{233}U), a fission reaction may be sustained, which is the basis of an ADS. Here, the spallation-neutrons cause fission in the fuel, and the process is assisted by further fission-neutrons. Since an ADS burns fuel which lacks a sufficiently large fission-to-capture ratio for neutrons to maintain a fission chain reaction, the whole assembly may be instantly turned-off, merely by shutting-off the proton beam, in contrast to inserting control rods to absorb neutrons and make the fuel assembly subcritical, as is necessary in conventional fission-reactors. The latter is often stressed as a key safety feature of an ADS, and while it is true that fission could be stopped almost instantly in an emergency, the substantially greater threat from decay heat would remain, as at Fukushima.

3. Thorium utilisation

To breed ^{232}Th to ^{233}U, a driver fuel is needed – either plutonium or enriched uranium – otherwise there are insufficient neutrons generated to keep the process going. As is the case for uranium, in order to use all of the thorium as a fuel, fast neutron reactors are required in the system. The concept[9] of using an ADS, based on the ^{232}Th–^{233}U fuel cycle, is due to Professor Carlo Rubbia, in which the core would be mostly thorium, and located near the bottom of a tank 25 metres high, and containing around 8,000 tonnes of molten lead or lead-bismuth at a high temperature – this is the "primary coolant", which circulates by convection around the core. A beam of high-energy protons from the accelerator, would be focussed along a beam-pipe to the spallation target, inside the core, where the spallation neutrons enter the fuel and transmute the thorium into protactinium, the decay of which forms the fissile ^{233}U. The neutrons also induce fission in uranium, plutonium and possibly any transuranic elements that are present, with an according release of energy. Thus, a 10 MW proton beam might produce 1500 MW of heat. This would accord with a generation of 600 MWe of electricity – allowing for the usual Carnot Cycle energy losses – some 30 MWe of which would be needed to drive the accelerator. However, existing accelerator technology can only produce a proton beam with an energy of 1 MW. A reactor of this kind is sometimes referred to as an energy amplifier. There is a UK–Swiss design for an accelerator-driven thorium reactor (ADTR) which has advanced to the stage of a feasibility study, and involves a 600 MWe lead-cooled fast reactor. The proposal is for a 10-year self-sustained thorium fuel cycle, using plutonium as a fission starter, with both the spallation target and the coolant being provided by molten lead. For actual power production, the accelerators would need to be increased in power by an order of magnitude, and massively in terms of reliability (so, I am told). In 2008, a study was made in Norway which compared the advantages and disadvantages of an ADS fuelled by thorium – relative to a conventional nuclear power reactor – from which it was concluded that such a system would be unlikely to be operating in the next 30 years[9].

An alternative technology to the ADS, is the LFR, which is discussed in detail at http://energyfromthorium.com/, and reading this site has convinced me that the LFR may provide the best means to achieve our future nuclear energy programme. As already noted, thorium exists naturally as ^{232}Th, which is not of itself a viable nuclear fuel. However, by absorption of relatively low energy "slow" neutrons, it is converted to (protactinium[10]) ^{233}Pa. The latter either decays further to ^{233}U or captures another neutron, which converts it to the non-fissile ^{234}U. ^{233}Pa has a relatively long half-life of 27 days and a high cross-section for neutron capture (the so-called "neutron poison"), hence, instead of undergoing a simple and fast decay to ^{233}U, a significant fraction of the ^{233}Pa consumes neutrons which convert it to non-fissile isotopes, so attenuating the reactor efficiency. To avoid this, the ^{233}Pa must be extracted from the active zone of the thorium LFR, so that it may be allowed mainly to decay to ^{233}U. In one scenario, this may be achieved by using columns of molten bismuth, with lithium dissolved in it, that are several metres high. The function of the lithium is to selectively reduce protactinium salts to metallic protactinium, which is then extracted from the molten-salt cycle, the bismuth acting mainly as a carrier (solvent). Bismuth has a low melting point (271 °C), a low vapour pressure, lithium and actinides are quite soluble in it, and it is immiscible with molten halides[10]. The "breeding" cycle can be initiated using plutonium, say, to provide the initial supply of neutrons, and indeed the LFR could provide an efficient way of disposing of weapons-grade plutonium and heavily-enriched uranium from the world's stockpiles, producing useful energy in the process.

The LFR makes *in-situ* reprocessing possible, and much more easily than is the case for solid-fuel based reactors. To date, there have been two working LFR's built[11], and if implemented, the technology would avoid using uranium–plutonium fast breeder reactors, which need high energy "fast" neutrons to convert ^{238}U, which is not fissile, to ^{239}Pu which is. The design of the LFR is inherently safer and does not require liquid sodium as a coolant, while it also avoids the risk of plutonium getting into the hands of terrorists. I maintain my reservations about how long other resources, *e.g*. oil and gas will last, with which to mine and process either uranium or thorium, but if the latter appears viable in the longer run, I suggest that molten salt (liquid fluoride) reactors might provide a more viable approach than the far more complex (and as yet untested) accelerator-driven systems.

More thorium would doubtless be found if it were looked for hard enough, and so the basic raw material is not at issue. Being more abundant in most deposits than uranium, its extraction would place less pressure on other fossil fuel resources used for mining and extracting it. Indeed, thorium-generated electricity could be piped-in for that purpose. Despite these apparently impressive advantages, the new build of infrastructure would be massive, to switch over entirely to thorium; as it would be to convert to any other new technology, on the grand scale, including hydrogen and biofuels, with attendant costs of materials, energy, labour and other resources. Indeed, this provides the mass of resistance that is to be expected over the implementation of all kinds of new technology. My belief is that, once the "liquid fuels crisis" occurs, which will be the major, and most immediate, consequence of a decline in world conventional crude oil production, "peak oil", we may be able to produce liquid fuels from coal, possibly using electricity produced from thorium. The problem of nuclear waste is expected to be lessened through the use of thorium, since fewer actinides result from its fuel cycle compared with that from uranium. It is not clear how the development of thorium energy in Europe will be funded, if at all, since much of the Euratom budget is being spent on the ITER nuclear fusion project, and the remainder on uranium-based fission programmes[12].

4. Oak Ridge National Laboratory molten salt breeder reactor.

^{232}Th, ^{235}U and ^{238}U are radionuclides that predate the formation of the Earth some 4.5 billion years ago, and were created in the cores of dying stars through the r-process being dispersed galactically by supernovas. Around half[13] the internal heat of the Earth is produced from the decay of these radioactive elements, along with ^{40}K, and it is this effect, unknown at the time of Lord Kelvin, that led him to conclude this planet to be much younger than it actually is, at between 20 million and 400 million years, rather than the currently accepted value of 4.54 (±0.05**)** billion years[14]. As a result of both historical and technical factors, each of the above type of nuclide tends to be associated with different kinds of reactor: across the world, the principal nuclear fuel is ^{235}U, as it has been since the dawn of the nuclear age, and this is usually used in light water reactors; $^{238}U/^{239}Pu$ has been used mainly in liquid sodium cooled, fast breeder reactors and CANDU Reactors; $^{232}Th/^{233}U$ is thought best suited to fuel molten salt reactors (MSR)[11].

The MSR at Oak Ridge National Laboratory (ORNL) (Figure 1) was pioneered by Alvin M. Weinberg, where two prototype molten salt reactors were successfully designed, constructed and operated. These were the Aircraft Reactor Experiment (ARE) in 1954 and MSR experiment (MRSE) which ran between 1965 and 1969, and in both cases, liquid fluoride fuel salts were used. Fuelling with ^{233}U and ^{235}U was demonstrated during separate test runs. A proposed molten salt breeder reactor (MSBR) was designed at ORNL, during the

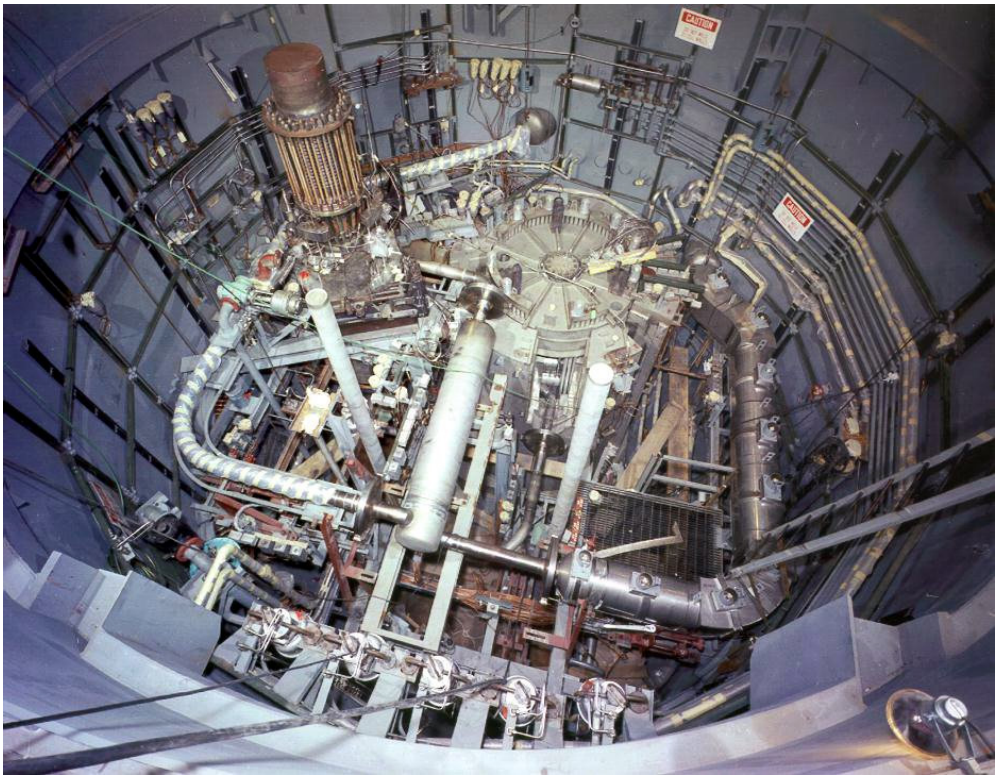

Figure 1 *Molten salt reactor at Oak Ridge National Laboratory.*
http://upload.wikimedia.org/wikipedia/commons/a/ab/MSRE_Reactor.JPG

period 1970–1976, with $LiF-BeF_2-ThF_4-UF_4$ (in the relative proportion: 72:16:12:0.4) as its fuel, and with a graphite moderator, to be replaced every four years, with $NaF-NaBF_4$ as the secondary coolant, and a peak operating temperature of 705 °C. However, the MSR programme was closed in the early 1970s, in favour of the liquid metal fast-breeder reactor (LMFBR). Research into MSRs then lapsed in the USA, and as of 2011, the ARE and the MSRE remained the only molten-salt reactors ever operated. The MSBR project received funding until 1976, equivalent to $38.9 million from 1968 to 1976 (compensated for inflation to the monetary $ value in 1991)[11].

5. Rare earth elements and thorium power

Thorium is present in the ores of rare earth elements, and indeed, there is more thorium available from this source than the current world demand for it[15]. As a consequence of its radioactive nature, a hazard is posed from its content in waste produced by the processing of rare earth oxides. However, as we have noted, thorium could be bred into a nuclear fuel and most simply used in a liquid fluoride reactor (LFR), rather than burying it underground in concrete. 97% of world market supplies of rare earth elements (REEs) come from China and look to become insecure in regard to meeting "green" energy targets, since supplies of REEs are scheduled to be retained for Chinese home energy projects. REEs are essential raw materials for the fabrication of high-performance magnets in hybrid cars and wind-turbines. The REE

distribution in monazite sands is around 45–48% cerium, 24% lanthanum, 17% neodymium, 5% praseodymium, along with minor quantities of samarium, gadolinium and yttrium. Europium concentrations tend to be low, in the region of 0.05%, and very low concentrations of the heaviest lanthanides in monazite accord with the term "rare" earth for these elements, with correspondingly high prices. The thorium content[16] of monazite is variable and can be as high as 20–30%, although commercial monazite sands typically contain 6–12% thorium oxide. In January 2013, a controversial REE processing plant was commissioned by the Australian based mining company Lynas in Malaysia[17], where it is argued that environmental protection laws are less rigorous than in Australia. The plant is predicted to produce one third of global demand for REEs, hence breaking the Chinese monopoly.

6. Thorium-based power: positive and negative features

6.1 Positive aspects[4]

Although precise knowledge of the true amount of reserves, globally, is limited, thorium is estimated to be about 3–4 times more abundant than uranium in the Earth's crust. Very likely, further sources of the material would be found, if they were sought with sufficient assiduousness, noting that the EROEI would fall with the decreasing grade (thorium content) of particular ores. Current demand for thorium (mostly not for power generation) has been satisfied as a by-product of rare-earth extraction from monazite sands, but demand for the metal is relatively low in comparison with that for REEs, so that the thorium ends-up as radioactive waste from processing this mineral. Since thorium consists of a single isotope (^{232}Th), it can be employed in thermal reactors without requiring isotope separation, unlike natural uranium, from which the fissile ^{235}U must be separated and enriched for use as a nuclear fuel in fission-reactors.

Relative to uranium-based fuels, thorium offers a number of appealing features: the thermal neutron absorption cross section (σ_a) is about three times, and the resonance integral (average of neutron cross sections over intermediate neutron energies) about one third for ^{232}Th of the respective values for ^{238}U, meaning that the conversion of thorium is more efficient in a thermal reactor. Although the thermal neutron fission cross section (σ_f) of the resulting ^{233}U is comparable to ^{235}U and ^{239}Pu, it has a much lower capture cross-section (σ_γ) than the latter two fissile isotopes, providing fewer non-fissile neutron absorptions and a better neutron economy. Finally, the ratio of neutrons released per neutron absorbed (η) in ^{233}U is >2, and over a wide range of energies, which covers the thermal spectrum, meaning that thorium-based fuels might be used in a thermal breeder reactor.

Because the ^{233}U produced in thorium fuels is always contaminated with ^{232}U, thorium-based nuclear fuel has an inherent proliferation resistance. ^{232}U cannot be separated from ^{233}U by chemical means, and it has several decay products which emit high energy gamma radiation, alerting to the presence of such materials, *e.g.* "a bomb in a suitcase". ^{233}U can be denatured by mixing it with natural or depleted uranium, meaning that before it could be used in nuclear weapons, isotopic separation would be necessary.

On a timescale, roughly of 10^3 to 10^6 years, the radiological hazard of conventional uranium-based used nuclear fuel is dominated by plutonium and other minor actinides, but once these have decayed, long-lived fission products once more make a significant contribution. A single neutron capture in ^{238}U is sufficient to produce transuranic elements, whereas six such captures are generally necessary to so convert ^{232}Th. 98–99% of the nuclei

in the thorium-cycle fuel would fission either at the ^{233}U or ^{235}U stage, thus resulting in fewer long-lived transuranics. As a result, in mixed oxide (MOX) fuels, thorium offers an advantage over uranium, in minimising the generation of transuranics while maximising the destruction of plutonium.

The advantages of thorium in nuclear waste management, while noting that it produces far less in the way of transuranics, are mitigated by the production of ^{231}Pa. also an α-emitting actinide, with a half-life of 3.3×10^4 years, along with the full range of fission products. It is the simple presence of the latter, more than their amounts, that is the problem. Indeed, the chemical intractability of thorium oxide makes it a good waste form in its own right, although it does almost preclude volume reduction by separating the few percent of genuine waste from unused material. That said, direct disposal eliminates the plant and secondary waste production incurred in such separation, which naturally is equally available for uranium.

6.2 Negative aspects[4]

The application of thorium as a nuclear fuel poses a number of problems, particularly for solid fuel reactors. Since natural thorium contains no fissile isotopes, it is necessary to add fissile material ^{233}U, ^{235}U, or plutonium, in order to attain criticality. Along with the high sintering temperature necessary to make thorium-dioxide fuel, this is a complicating factor in fuel fabrication. ORNL experimented[11] with thorium tetrafluoride as a fuel component, in their run of a molten salt reactor from 1964 to 1969, which was far easier both to process and to separate from contaminants, which slow-down or actually halt the chain reaction.

In an open fuel cycle (using ^{233}U *in situ*), a higher burn-up is necessary to achieve a favourable neutron economy. Although thorium dioxide performed well at burn-ups of 170,000 MWd/t and 150,000 MWd/t at Fort St. Vrain Generating Station (http://en.wikipedia.org/wiki/Fort_St._Vrain_Generating_Station) and AVR (http://en.wikipedia.org/wiki/AVR_reactor) respectively, achieving this in light water reactors, which are the vast majority of existing power reactors, worldwide, is a challenge. In a once-through thorium fuel cycle, the residual ^{233}U constitutes long-lived radioactive waste.

The main objection on the part of the nuclear industry to thorium is its radiotoxicity, greater by an order of magnitude than that of uranium, in consequence of the presence of ^{232}U and decay products, therefrom. Thus, a completely new infrastructure would be required, involving more stringent dust control.

The thorium fuel cycle requires a relatively long interval to breed ^{232}Th to ^{233}U. The half-life of ^{233}Pa is about 27 days, which is an order of magnitude longer than the half-life of ^{239}Np, as occurs in breeding from ^{238}U to ^{239}Pu. As a result, substantial quantities of ^{233}Pa, which is an effective absorber of neutrons, build up in thorium-based fuels. Thus, instead of undergoing a simple and fast decay to ^{233}U, a significant fraction of ^{233}Pa consumes neutrons which convert it to non-fissile isotopes, *e.g.* ^{234}Pa, and this attenuates the reactor efficiency. Therefore, the ^{233}Pa must be extracted from the active zone of the thorium LFR, so that it may be allowed mainly to decay to ^{233}U. Eventually, the ^{233}Pa would breed into fissile ^{235}U, but this process requires overall two more neutron absorptions, and hence occurs at the further expense of the neutron economy. The likelihood of transuranic production is also increased.

Although the presence of ^{232}U would inhibit its use in a nuclear weapon, ^{233}U was once so employed, as part of a bomb core in the MET (Military Effects Test) blast during "Operation Teapot" in 1955, though the energy yield was appreciably less than had been anticipated.

7. Current thorium projects[18]

Research and development of thorium-based nuclear reactors, primarily the liquid fluoride thorium reactor, MSR design, has been or is currently ongoing[18] in the USA, UK, Germany, Brazil, India, China, France, the Czech Republic, Japan, Russia, Canada, Israel and the Netherlands.

- **China**. Using components produced by the West and Russia, it was reported early in 2012 that China planned to build two prototype thorium molten salt reactors by 2015. A budget for the project was established at $400 million, which will require 400 workers. China has also finalised an agreement with a Canadian nuclear technology company to develop improved CANDU reactors using thorium and uranium as a fuel.
- **India**. This is the "only country in the world with a detailed, funded, government-approved plan" to focus on thorium-based nuclear power. In late June, 2012, India announced that their "first commercial fast reactor" was near completion and would rely on thorium for its fuel. The nation plans to develop up to 62, mostly thorium-based reactors, intended to be fully operational by 2025.
- **Norway**. In Norway, the privately-owned company, Thor Energy, announced in late 2012, that in collaboration with the government and Westinghouse, it will start a 4-year-long trial to employ thorium as a nuclear fuel in one of its existing nuclear reactors.
- **USA.** In its report to the Secretary of Energy, in January 2012, the Blue Ribbon Commission on America's Future notes that a "molten-salt reactor using thorium [has] also been proposed", while in the same month, it was stated the US Department of Energy is "quietly collaborating with China" on a molten salt reactor using thorium fuel.
- **Japan.** In the aftermath of three meltdowns at nuclear power plants in 2011, Japan utility Chubu Electric Power, wrote in June, 2012, that they are considering thorium as "one of future possible energy resources."
- **Israel**. Researchers from Ben-Gurion University in Israel and Brookhaven National Laboratory in New York began, in May 2010, a collaboration to develop self-sustaining thorium reactors, "meaning one that will produce and consume about the same amounts of fuel."
- **UK.** In Britain, a member of the House of Lords, Bryony Worthington, is actively promoting thorium, which she refers to as "the forgotten fuel". However, the UK's National Nuclear Laboratory has published a paper on the thorium fuel cycle, finding that, "the thorium fuel cycle does not currently have a role to play," in that it is "technically immature," and "would require a significant financial investment and risk without clear benefits," and which are "overstated." The environmental group, Friends of the Earth UK, are of the opinion that research into thorium-based power might be "useful" as a fallback option.

References

1. http://en.wikipedia.org/wiki/Thorium
2. Data taken from Uranium 2007: Resources, Production and Demand, Nuclear Energy Agency (June 2008), NEA#6345 (ISBN 9789264047662). The 2009 figures are largely unchanged. Australian data from Thorium, in Australian Atlas of Minerals Resources, Mines & Processing Centres, Geoscience Australia.
3. http://ergobalance.blogspot.co.uk/2006/06/thorium-instead-of-uranium.html.
4. http://en.wikipedia.org/wiki/Thorium_fuel_cycle.
5. http://en.wikipedia.org/wiki/Peak_uranium
6. http://nucleargreen.blogspot.co.uk/2008/03/edward-teller-listens-as-eugene-weigner.html
7. http://pbadupws.nrc.gov/docs/ML0930/ML093090346.pdf
8. http://www-pub.iaea.org/MTCD/publications/PDF/TE_1450_web.pdf
9. http://www.world-nuclear.org/info/Current-and-Future-Generation/Accelerator-driven-Nuclear-Energy/#.UVA32VevPRk
10. http://en.wikipedia.org/wiki/Protactinium
11. http://en.wikipedia.org/wiki/Molten_salt_reactor#Oak_Ridge_National_Laboratory_molten_salt_breeder_reactor
12. http://blogs.telegraph.co.uk/finance/ambroseevans-pritchard/100022190/last-chance-to-protest-before-the-eu-snuffs-out-thorium-energy-in-europe/
13. http://news.sciencemag.org/sciencenow/2011/07/earth-still-retains-much-of-its-.html
14. http://en.wikipedia.org/wiki/Age_of_the_Earth
15. http://www.the-weinberg-foundation.org/2012/11/20/how-to-manage-the-dirty-side-of-thorium-and-assure-its-global-supply/
16. http://www.world-nuclear.org/info/Current-and-Future-Generation/Thorium/#.UVGnXlevPRk
17. http://www.miningaustralia.com.au/news/lynas-ramps-up-rare-earth-processing-in-malaysia
18. http://en.wikipedia.org/wiki/Thorium-based_nuclear_power#World_sources_of_thorium